APPLICATIONS OF SWIMMING POOL REACTORS

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SUMMARY

This paper relates to the study of swimming pool reactors
in the light of their application. Their characteristics,
as a source of radiation, are highlighted. The available
fluxes, superior to 10^{13} n/cm^{2}s, offer very great experi-
mental possibilities. The influence of experimental programs
on the basic concept of the swimming pool reactor is briefly
examined.

At present, there are about sixty swimming pool reactors in the world, either in operation, under construction, or in advanced design stage; and this is the best indication of the great interest shown in this type of research reactor. Indeed, within the framework of the nuclear energy development, it offers such a combination of advantages and possibilities that it should be given first choice in preference to any other kind of research reactor of equal power.

Its operational flexibility permits the carrying out of almost every possible experiment within the range of the available fluxes (up to 5.10^{13} n/cm^{2}s), and this is important when we consider the fact that the purchase of a research reactor is often decided upon before the experimental programs are even established. This flexibility results from the possibility that the configuration of the active lattice can be varied, and the reactivity adjusted to the importance of the experiments in progress. In addition, owing to the fluidity and transparency of the shielding, experiments can be made directly in the core, particularly in the central section of greater intensity, thus providing an appreciable gain on the fast neutron flux.

Easy accessibility: Most of the experimental work can be carried out visibly and manually from the top of the tank.

Built-in safety: Even if an excess of reactivity were to take place this would, at worst, cause the cooling water to reach the boiling point.

These essential qualities make the swimming pool reactor the ideal laboratory reactor within the wide range of experimental possibilities on average flux. Its purchase is within the financial means of large research centers and universities, organization groups, industrial laborayories, and countries entering the field of nuclear energy. A joint purchase can be contemplated with interest, and in preference to that of a small standard reactor, the flux of which, not exceeding 10^{11} n/cm^{2}s, remains very limited in its application. Moreover, the difference in price is less evident when we thoroughly examine the eventual reduction of investments by simplifying the general facilities. In this respect, nothing should be neglected by the manufacturer to widen, in the commercial domain, the range of potential customers.

THE SWIMMING POOL REACTOR, RADIATION SOURCE

The swimming pool reactor is a radiation source, and as such, its main features are the fluxes it offers together with the experimental volume at which they become operational

Radiation Nature

When we examine the radiations in a reactor in view of their experimental utilization, we mainly refer to neutrons and gamma-rays:

- The neutrons produced in the reactor have an energy range from 0 to about 15 MeV, therefore very wide. Since the kinds of research, the methods and the equipment used vary according to the energy of radiation applied, we divide the neutron spectrum,

somewhat arbitrarily, into three distinct groups: <u>fast</u> neutrons
(from 1 to 15 MeV), <u>resonance</u> or <u>epithermal</u> neutrons (from 0.4 eV
to 1 MeV), and <u>slow</u> or <u>thermal</u> neutrons (around 0.025 eV).

- The <u>gamma rays</u> are emitted in the reactor, either during
the fission process, with energies reaching 6 MeV, or at the
time of the capture of the neutrons by the reactor materials. We
can also use, as gamma-radiation sources, fission products con-
tained in the radiated fuel elements, or artificial elements
produced in the reactor.

Flux Intensity

A swimming pool reactor with an average operating power
of 1000 kW delivers a maximum thermal flux of about 10^{13} n/cm^{2}s.
The corresponding collision virgin flux and the fast flux are,
at the center of the core, $1.5.10^{13}$ and 5.10^{13} n/cm^{2}s respectively.
They are comparable to those of a heavy water reactor ten times
more powerful, in which they can only be obtained inside the fuel
rods. This heavy percentage of fast neutrons for a given thermal
flux, inherent in this type of enriched uranium lattice, moderated
with ordinary water, is an advantageous feature of the swimming
pool reactor, particularly enhanced by the present tendency to
operate in increasingly higher energy areas.

The flux of gamma-rays is of the same order as the
fluxes of fast neutrons, $5.10^{13}\gamma$/cm^{2}s for an average power of
1000 kW, i.e. 2.10^8r/h (roentgen/hour).

Broadly speaking, such nominal fluxes are sufficient
for most experiments. But for a good many of them, what matters
is the integrated flux $\int \varphi dt$ (flux multiplied by time, when the
flux is constant). The initial intensities supplied by the

swimming pool reactors are suitable for irradiations up to 10^{17} or 10^{18} n/cm^2 (the studies of materials reliability under irradiation require higher nominal fluxes in order to obtain substantial effects within reasonable times). Yet when we consider the fact that it is possible, with little difficulty and at reasonable cost, to raise the power of swimming pool reactors to 2.3 MW and even to 5 MW, its flux, which is in direct proportion to the power, finally reaches intensities which come pretty close to those of more powerful reactors. When we combine these possibilities to the ingeniosity of experimenters, then the majority of the work can be successfully carried out on mean fluxes.

Flux Distribution

In a swimming pool reactor of the MELUSINE type, the fluxes are uniform enough for the whole of the core, with a central section - approximately 10 dm^3 (0.35 cf), of greater intensity for the fast flow. This latter can be used for several simultaneous experiments, and eventually improved by means of expedients in the loading lattice. Outside the active core, the fast neutrons rapidly disappear, many gamma-rays subsist, and the thermal flux is considerably weakened (3.10^{11} n/cm^{2}s at 10 cm from the core; 3.10^{11} n/cm^{2}s at 20 cm from the core for 1 MW).

The reactor simultaneously produces radiation of varied nature and energy, which must be selected in the desired range energy by means of filter systems.

Some experiments on fast or thermal neutrons are affected by the interference of resonance neutrons. When pure fast neutron fluxes are necessary, a converter can be used; in other words, we can irradiate outside the core a 235 uranium plate

with a well-thermalized beam; the restored fast flux, though
many times higher than the initial thermal flux, does not yet
reach the intensity existing in the center of the core, and the
converters are difficult to set up. In the case of experiments
requiring uncontaminated slow neutron fluxes, provisions can
be made for a scattering column called "thermal column" (usually
graphite or heavy water) which intensifies the moderating effect,
and which, situated in the vicinity of the reactor or in a
channel, becomes the seat of a predominantly thermal flux.

Uncontaminated gamma-ray fluxes may be obtained by
use of a reflector, and cadmium filters which absorb the thermal
neutrons. Should fluxes of great density be needed, an indium
loop can be installed. This material is a great absorber of
neutrons, and by making it circulate in and out of the core in a
liquid form (sulfate solution or gallium-indium with a low
melting point), it activates itself, releasing gamma-rays of great
energy. The continuous source thus created can, in the case of
indium sulfate, for instance, reach 100,000 curies per liter of
solution.

Experimental Facilities

Following are the means available to carry out measure-
ments and irradiation in a reactor:

- The primary task of the swimming pool reactor is to permit
the experiments to be immersed from the top of the tank, more or
less in the vicinity of the core. With this method, it is possible
to obtain full benefit from the fluidity and transparency of the
shielding and from the free access to the surface of the water.
The instruments and samples are immersed in the water, either

directly or in water-tight boxes. Some handlings by immersion
require the use of special cells, adapted to the pressure and
temperature of the tank. Loops can also be provided in order to
insure the continuous circulation of products to be irradiated,
in and out of the core or in its vicinity.

- The channels are used to permit the escape into the air of
directed beams necessary for particular nuclear physics experi-
ments. The obligation to operate in channels for these experiments
results partly from the fact that the measuring instruments are
designed to work on horizontal beams; on the other hand, should
subsequent developments take place, the possibility is not at
all excluded of operating in tilted or vertical channels, sub-
merged from the top of the tank. The channels are also used
to perform irradiations.

Despite the accepted tradition which makes the channels
the main attribute of the research reactor, it is worthwhile
pointing out that the majority of experiments can be carried
out by immersion, and that this method offers great advantages
over channel or rigid loop handlings:

- Considerably lower price (a channel handling requires in
most cases a special plug - very expensive, with adequate
unloading and dismantlihg means).

- Fabrication time of the system greatly reduced.

- Easy modification of the irradiation tank, the liquid
shielding shutting automatically on the system whatever its
profile.

- Easy dismantling under water once the core has been removed.

- Greater useful volume.

- The reactor system can be moved easily in operation, either at maximum power or at limited power, provided that its anti-reactivity be low, which is impossible when working in channel.

- Possibility of maintaining a shielding for the handling of the material being removed from the core, and of making additional measurements outside the flux.

Swimming pool reactors can be equipped with several other types of experimental systems, such as pneumatic tube, thermal column, neutron transparent "window," activated water loop, hot cell for handling instruments and radioactive products. The irradiated fuel elements, stocked in storage pits, are used as a source of gamma radiation.

Anti-reactivity of Handling Operations

Most of the experimental systems located against the core of a swimming pool reactor of the MELUSINE type, for instance, have very low effects on reactivity. This is explained by the use of aluminum, which is a low absorber, for containers, and of irradiating fuels which have neutron properties similar to those of water. It should be mentioned, however, that since the scattering length of thermal neutrons in the water is small, a few centimeters of water are sufficient from the reactivity standpoint, to "isolate" an experimental system from the reactor itself.

Applications

Before going into the detailed chapter of experimental programs classified according to ultimate use, such as research,

industry, and education, a brief outline of the distribu-
tion of these programs should be made from the nuclear stand-
point as a function of the nature and energy of applied radia-
tions:

Techniques using slow neutrons have been developed
from the very beginning of the research reactors, because of
the intensity of the available flux, their readiness to yield
beams, their great wavelength and cross sections. They are
mainly related to neutron physics and optics, ws well as to
the production of artificial radioelements. Experiments are
conducted within the core and with beams directed into the
channels.

Resonance neutrons are used for the studies of cross
sections. As a matter of fact, only energy neutrons of up to
1 keV can be used to determine distinct resonances for atomic
weights above 100. Whenever the study of a fairly wide energy
range has to be done, we work within the core; experiments on
monoenergetic neutrons after filtration are conducted in the
channels.

Although the fission neutrons show a spread in energy
of several MeV, they are becoming increasingly popular as an
experimental source, because of the high intensities available.
They have proved to be extremely useful for the study of solid
state physics, and under radiation in the field of chemistry.

Gamma radiation is a fundamental basis for much of
the pure physics work relating to its interaction with the
materials nuclei, its physico-chemical effect on the materials,

and its biological effect (health, genetics, medicine, radio-
therapy, agriculture, etc). Depending on the case, the oper-
ations are conducted directly within the reactor, or from the
sources produced by the reactor, such as artificial radioelements
or irradiated fuel elements.

RESEARCH AND EXPERIMENTATION

The experiments of pure and applied sciences which
may be conducted on swimming pool reactors belong to several
disciplines: physics, chemistry, metallurgy, reactor engineering,
medicine, biology, etc. Among them are some which are directed
toward the more or less direct utilization of radiation on an
industrial scale.

PHYSICS

Nuclear physics is interested in the swimming pool
reactor for the spectrometry of neutrons and gamma rays, the
neutron optics, and the measurements of nuclear parameters.
Another domain now in great expansion is that of solid state
physics, which finds in the high fluxes of fast neutrons an
efficient and accurate means of investigation.

Nuclear Measurements

The nuclear measurements of spectra and cross sec-
tions require nominal intensities rating from 10^{12} to 10^{13} n/cm^{2}s.
We generally proceed by comparison with standards of cross
sections, velocity or flux intensity, which are themselves
easily measured in absolute value.

With the beam methods, a parallel beam of neutrons is

emitted from the reactor and the sample of the material to be examined is placed in its field. It is usually necessary to operate on a monoenergetic beam, i.e. in a very narrow band around the desired value.

This selection is accomplished by means of various filtration, scattering and detecting systems, particularly sensitive in a given region, or else by means of methods derived from two processes of crystal spectrometry: time-of-flight measurements, and crystal spectrometry.

The measurement by time-of-flight involves the electronic measurement of the flight time - a few microseconds - of a burst of neutrons on a given path. Each burst, produced by a mechanical selector located at the outlet of a collimator, consists of neutrons of various energies in the selected range; depending on their energy, these reach the detector, located at the end of the path, at different times. Many velocities can be measured simultaneously, and the sensibility of the electronic devices permits energy measurements up to several thousands of electron volts (KeV).

In crystal spectrometry, we make the most of the wave properties of neutrons: by reflected in the same direction; through suitable cutoff and directing of the crystal, the desired monoenergetic beams are obtained.

These methods use well-collimated beams of thermal and resonance neutrons with intensities of about 10^8 n/cm^{2}s. Operation at a 100 kW level is the lower limit for such experiments.

For measurements within the core, samples are inserted into the active lattice, while the effect on reactivity is observed. This is how we measure the material absorption cross sections which are very important in calculating the neutron balances in the reactors. Fluxes of 10^9 n/cm^{2}s, corresponding to a power level of 100 W, are sufficient here. With the "static" method, the control rods of the reactor are locked on, and the sample is inserted into the core for a time, while the behavior of the reactor is recorded and studied; this method presents the disddvantage of being affected by the reactivity fluctuations caused by the variations of various factors such as temperature, mechanical distortion, lattice vibration, etc. The "dynamic" or swing measurement method, most widely used because of its accuracy, is based on the fact that if two materials have close cross sections, the difference between them may be measured by placing each alternately in the core and in a zero flux area. The two samples, the test tube and the test specimen, are placed in an oscillator moved in and out of the core, according to the amplitudes and frequencies selected. The MINERVE reactor, at the "Centre d'Etudes Nucléaires de Fontenay-aux-Roses," has been designed to that effect.

Another method of nuclear measurement if based on the phenomenon of activation of many materials by capture of neutrons, the thermal ones in particular. The study of activation spectra, the nuclei excitation, the emission of particles, and their correlation, are the subject of much fundamental research work. It plays a basic part in the production of artificial radioelements, and in

the development of analytical chemistry methods which will
be discussed later on. In the measurements by activation,
a thin sample of the material is placed in the flux, while
its saturation activity is measured. Fluxes of about 10^6 n/cm^{2}s,
with thin foil samples of material with microscopic cross
sections that are less than 1 barn (10^{-24}cm^2), give adequate
saturation counting rate. In the case of activation by fast
neutrons, fluxes of higher intensity are necessary, because
the activation cross sections for fast neutrons are much
smaller than those for thermal neutrons. Since it is difficult
to operate directly in the core where the fission flux is
mixed to resonance neutrons, a converter with an incident
thermal flux of 10^9 n/cm^{2}s is generally used.

Solid State Physics

The high-energy particles such as fast neutrons,
electrons or gamma-rays, create in the solid materials composed
of a crystalline structure, lattice modifications, atom dis-
placements, or interstitial imperfections, commonly described
by the term "irradiation effects." Their study now represents
an important part of the solid state physics. These imperfec-
tions affect the physical properties of the materials, and
among them, of course, those which are most sensitive to the
crystalline arrangement, such as brittleness, electrical-resis-
tivity, thermal conductibility, magnetism, etc. Thorough theoret-
ical research work is being devoted to the study of the irradiation
effects mechanism and to the incidence of the imperfections of
the crystalline lattice on the normal properties of solids.
This research work is a prelude to behavior studies under pro-
longed exposure of materials to be used for the construction of

reactors and experimental equipment.

Irradiation experiments require integrated doses ranging from 10^9 to 10^{20} n/cm^2 or γ/cm^2. In most cases, it is better to apply high-intensity fluxes during short times. Those at our disposal in the swimming pool reactors with average power (1000-1200 kW) are sufficient for most of the irradiations (organic materials, rubber, semi-conductors). Work on metals and alloys generally requires a nominal flux of 10^{14} n/cm^{2}s.

In order to benefit from the maximum intensity, the samples to be irradiated are placed in the central region of the core. However, the heating of the samples exposed to the effect of radiations creates within their crystalline lattice a thermal motion which disturbs the irradiation effect. Thus we could be led to operate in experimental cells maintained at very low temperature in order to freeze, so to speak, the irradiation effect. Nitrogen (80°K), hydrogen (20°K) and helium (4°K) could be used as a cooling fluid. The development of such loops is a complex one, but the advantage of irradiating under high intensity flux prevails and justifies the search for such solutions.

The nuclear solid state physics includes also the analysis of crystalline structures by means of techniques making use of the optic properties of neutrons. Incident fluxes on the order of 10^8 n/cm^{2}s on the crystal are necessary.

Neutron **diffraction**, in addition to its utilization in crystal spectroscopy, is chiefly used for the study of crystalline lattices and their magnetic properties. The technique,

comparable to X-ray analysis, consists in directing onto the
crystal under consideration, a beam of monokinetic neutrons,
and in analysing the diffracted neutrons as a function of
the angle of incidence. The primary beam itself is obtained
through the diffusion, by means of a monocrystal, of the neutrons
coming out of the reactor. The advantage of the neutron diffrac-
tion prevails for two types of crystals: organic and magnetic,
which are difficult and even impossible to study by means of
X-ray.

The other optical properties of the neutrons such as
reflection, diffusion, and refraction, are also exploited for
experimental purposes. But, whereas in the case of diffraction
on crystal, beams with an angular scattering of several degrees
are used, here narrower beams are used. The thin beams permit
the study of slight variations of the index of refraction;
they are used for studies of grain structure, magnetic properties,
lattice distortions and imperfections.

NUCLEAR CHEMISTRY

The intense sources of neutrons, gamma and electrons
supplied by the swimming pool reactor represent outstanding
experimental means in the rapidly expanding field of radio-
chemistry. In the vast scope of its activities, the latter
embraces basic research (study and identification of fission
products, behavior of chemical systems under irradiation), the
production of artificial radioelements, activation analysis, and
the development of new processes in view of their industrial
applications.

Fluxes corresponding to an operating power of 100 kW, i.e. 10^{12} n/cm^{2}s, are sufficient for the performance of most radiochemistry work. Depending on the flux nature and intensity desired, the work is accomplished either inside the reactor (core and its vicinity, channels), or outside, from sources created in the reactor. The samples are loaded in capsules (aluminum or polyethylene) to the point of irradiation. When the elements in question are of the very short life type, a more efficient method consists in using a pneumatic circuit running through the reactor core and directly connected th the adjoining laboratory where the samples are immediately examined. Some experiments require the continuous circulation of the products to be irradiated, and make use of loops crossing the selected flux area.

Study and Production of Artificial Radioelements

Many materials, when exposed to the action of neutrons, are activated and transformed into radioactive isotopes. According to the type of nuclear reaction occurring:)n,γ) (n,ρ) (n,α), the radioelements produced are of a chemical nature similar to, or different from, that of the target element. Out of 102 elements, about 1400 radioactive species have been identified, while many others are constantly being discovered.

The application of radioelements is likely to be extended to many branches of research and industry, medicine, biology, radiotherapy, chemistry, metallurgy, technology, etc. This explains the importance of the research work now being devoted to their study and production. Since most of the isotopes under consideration have a short half-life, it is desirable to

produce them on the very spot of their utilization, and this
accentuates the advantage of having a local reactor adjacent to
the application laboratory.

The quantity of radioisotopes likely to be produced
in a reactor is dependent upon the reactivity available to that
effect. The main characteristic of the radioelements under con-
sideration is their specific activity, which varies directly
with the flux. The saturation is practically reached after an
irradiation time corresponding to about eight half-lives of the
formed element; at the end of a half-life, the activity yielded
is equal to roughly half of the saturation. The specific acti-
vity characterizes the ratio of the amount of radioactive atoms
to the total amount of atoms present in the radioisotope, this
latter being in fact a mixing of stable and active isotopes;
it is generally expressed in terms of curies per unit of mass of
the radioactive material. We thus realize, at least theoreti-
cally, that it is possible to increase in great proportions the
specific activity; the maximum would be reached for a radio-
element all the atoms of which would be radioactive. The
so-called "high specific activity" radioelements are prepared by
choosing the adequate nuclear reaction, by enriching the "acti-
vable" isotope target, or also through chemical separation after
irradiation (Szilard-Chalmers effect).

The great majority of known radioelements can be
produced within reasonable times in fluxes of 10^{12} n/cm^{2}s.
To obtain the required activity, there is a possibility of
"cheating" on the irradiation time or the target weight. The

half-lives of a good many of the radioelements are limited
to two days; below five minutes they are of negligible value;
beyond 100 days, their production is made easier with more intense
nominal fluxes (from 10^{13} to 10^{14} n/cm^{2}s.)

The needs in activity vary according to the experi-
ments, but one generally considers as a good average the value
of 0.1 microcurie per mg of natural element (which corresponds
to 3.7 x 10 decays/s mg).

Activation Analysis

Through the use of intensive sources of neutrons
provided by research reactors, analytical chemistry has developed
a new technique of analysis, based on the very high sensitivity
of radioactivity detection. It permits the dosage of element
trace in the materials with an accuracy never before achieved by
conventional procedures. The method consists in irradiating
together, under thermal flux, a sample of the material to be
analyzed, and a standard of the element to be assayed; the
comparison of the induced activities after irradiation, permits
the determination of the trace content of the element under
consideration. The measurement sensitivity depends largely
upon the activation section of the element to be detected, the
flux, and the characteristics of the induced activity; favorable
circumstances permit detections with 10^{-12}g. This method is
applied with success for organic materials and metallurgy.

CHEMICAL EFFECTS OF IONIZING RADIATIONS

The radio-induced reactions have been known for a
long time, but their real development took place only since the

release of intensive sources of radiations by nuclear reactors.
With only a few exceptions, this particular field is still in
an experimental stage. From a technical standpoint, however,
various radio-induced procedures have already proven their
interest or their superiority over conventional ways of production.
Although a serious economic barrier has to be overcome, the
possibilities of utilizing radiations in the domain of che-
mistry can be contemplated with great optimism. They are too
numerous to list here in their entirety, therefore, we shall
limit our discussion to those which, at the present time, are
most likely to be developed industrially, either because their
radio-chemical yield (number of molecules transformed by
absorbed eV) appears to be more economical than conventional
procedures, or because the radio-induced procedure gives products
which are of a higher quality or which possess specific proper-
ties which cannot be obtained by other means. These applica-
tions relate particularly to macromolecular chemistry, petro-
chemistry and catalysts.

Polymerization and Radiation Effects on Polymers

The great majority of polymerizations on free radicals
obtained through conventional techniques are also produced with
great efficiency by irradiation under fast neutron and gamma-ray
fluxes. Through this method, the radio-induced polymerization
of ethylene, silicons, polyesters, vinylacetate (and other esters),
etc., has been successfully achieved on an experimental scale.
Long chain polymers, obtained either by chemical or radio-induced
processes, are likely to undergo, under the effects of radiation,

modifications variable according to their substance. Some
will present a cross linking phenomenon with change of bonds
linking, to which can be attributed, in major part, the im-
proved characteristics of radio-induced polymers. The irradiated
polythene, for instance, the only material produced by radio-
chemical means in the United States on the industrial scale,
offers a stability under temperatures greatly increased by
radiations. On the other hand some polymers undergo a degra-
dation accompanied by a rupturing of bonds which has a totally
adverse effect on their properties; such is the case of Téflon,
Plexiglas, etc.

The vulcanization of rubbers also offers intriguing
prospects; up to the present time, only lots of thick or unu-
sually shaped objects, or those which require special physico-
chemical and mechanical characteristics, have been treated in
this manner. Recent work, however, has now made it possible
to think seriously of the profitable exploitation of radio-
chemical vulcanization.

In the field of organic materials, intensive work
in the study of the radio-chemical grafting of copolymers is
being carried out with great interest.

Organic Synthesis, Radiation Action on Hydrocarbides

The chloruration of aromatic hydrocarbides (benzine,
toluen, chlorobenzine), effected with good efficiency under
gamma radiations) is the best knwon of all the radiation appli-
cations in organic synthesis. The gamma rays have the advan-
tage of creating penetrating reactions throughout substantial

volumes, and of giving better products with pressure and temper-
ature conditions made more flexible; another advantage lies in
the possibility of operating continuously in and out of the flux,
and not by successive batches.

Organic synthesis offers also several other possibi-
lities such as radio-induced chloruration of benzine, which
yields a compound with marked insecticide properties, sulfoxy-
dation of hydrocarbides in order to obtain lubricants and soluble
detergents, production of phenol by oxydation of benzine,
oxydation of paraffins. Long range experimental programs are
now investigating the possibility of a direct treatment of oil
by fast neutrons and gamma rays, at the different stages of
conversion such as desulfuration, deshydrogenizatio n, poly-
merization, isomerization, aromatisation and cracking.

Radiation Effect on Catalysts

The heterogeneous catalysis is a basis for many
industrial processes, and plays a predominant part in numerous
biochemical reactions. Very little is known about the mechanism
of these reactions, though various methods of research (absorp-
tion, microscopy, X-rays, magnetic and electrical measurements)
have well contributed to shed light on the problem; however,
the development of nuclear sources led to new means of approach
which look more promising. In addition to the utilization of
radioactive tracers which permits thorough investigations into
the catalystic process, it seems that irradiation under intense
flux should greatly modify and intensify their catalytic proper-
ties. Gamma rays or a neutron-gamma mixture are used for most

of the nuclear experiments relating to heterogeneous catalysis.

METALLURGY

For the benefit of metallurgic research, we should recall the interest of activation analysis. We should also mention the utilization of radioactive tracers for numerous studies of corrosion, diffusion, distributions of traces, metallurgical processes, friction, wear, etc.

REACTOR ENGINEERING

The development of nuclear energy is linked to the solution of many technical problems which have to be studied in research and testing reactors meeting the operational conditions. The swimming pool reactor could contribute to the three following studies:

Shielding Studies

These are calculated from the neutrons cross sections and relaxation lengths. However, the analysis of radiation attenuation in materials is complex, and when the weight, cost and size factors have to be included in the shielding studies, it is necessary to support the calculations by means of tests performed on a substantial number of samples, and to effect direct measurements of the attenuation spectra.

The swimming pool reactor permits a direct and visible immersion into the samples pit in the vicinity of the core, or else dry tests behind an aluminum window (as in the TRITON reactor). The core can be moved at will in the tank according to the experimental requirements; direct handling of the samples, large

or small, from the top of the tank, greatly simplifies the operations.

Tests of Fuel Elements

Special loops, moved in and out of the core, pressure-and-temperature-conditioned, make possible the study of their behavior under conditions of temperature (sheath, corrosion), of the development of their nuclear properties and of their thermal efficiency under the conditions existing in the loop.

Behavior Study Under Material Radiation

It is a part of the physico-chemical effects of radiation, discussed in the preceding paragraphs, and, as seen, principally utilizes high fluxes of fast neutrons.

BIOLOGY

In all phases of biology, radiation and radioidotopes find a wide variety of applications:

- basic research on the action of radiation in the biological processes of the animal kingdom.

- vegetal photosynthesis utilizing the tracer properties of carbon 14.

- activation analysis of important elements for plant and animal life, and present in the form of trace.

- distribution and concentration of components in the vegetal systems (use of tracers Na^{24}, K^{42}, Cl^{38}, Cu^{64}).

- in agriculture, grain irradiation tests intended to increase the efficiency and quality of plants.

MEDICINE AND RADIOTHERAPY

Radioelements destined for medical use hold an important

place: P^{32}, Au^{198}, I^{131}, I^{128}, Cr^{51}, B^{10}, Cl^{38}, Br^{82}, Na^{24}, K^{42}, Co^{60}, Cu^{64}. These substances are used both in therapeutics and diagnostics. They must meet very strict criteria of purity and are subject to very severe physical, chemical and biological controls.

The cobalt therapy of cancer makes use of Co^{60} gamma rays. The treatment of cancer by direct exposure to intense fluxes of neutrons is also under consideration, and can be achieved with a swimming pool reactor specifically designed for that purpose.

INDUSTRIAL APPLICATIONS

From the industrial standpoint, the chief advantage of swimming pool reactors at the present time lies in the possibilities already stated:

- to produce innumerable artificial radioelements likely to find increasingly numerous applications in matters of analysis, measurement and detection, such as activation analysis, gamma-graphy, radioactive gauges, use of tracers in metallurgy, in the industrial circuits, in biology, medicine, etc.

- to develop new procedures and radiation-induced products (polymerization, vulcanization, processing of hydrocarbides, catalysis, etc) which should lead in the near future, if not to profitable results from the commercial standpoint, at least to the creation of improved products, or products having parti-wular properties.

- to study materials and equipment for the construction of forthcoming powerful reactors.

Another application of radiation, which is becoming
increasingly popular, and the subject of numerous experimental
programs, is the sterilization of foodstuffs and drugs. Doses
of 5 x 10^5 reps permit the lifetime of products under refrige-
ration to be prolonged appreciably. Doses of 2 x 10^6 reps can
destroy the micro-organisms causing damage, and the foodstuffs
can then be shelved without refrigeration. To this end, the
doses available in a swimming pool reactor operating at MW:
2 x 10^8 roentgen/h are largely sufficient.

PERSONNEL EDUCATION AND TRAINING

The development of nuclear energy, either as a private
or a national undertaking, requires the accelerated training of
an increasingly greater number of scientists, engineers and
specialized technicians. The universities and organizations
conducting nuclear courses, find in the swimming pool reactor
a formidable instrument of demonstration, for it combines
extreme safety and easy accessibility with great operating
flexibility. The possibility of varying, at will, the core con-
figuration in order to obtain critical and subcritical assemblies
is very appreciated for the study of physics and reactor engineer
ing, such as studies of nuclear parameters, divergence, power
rise, influence of control rods, lattice studies, determination
of the temperature coefficient, flux distribution, poisoning,
influence of materials structure and channels on reactivity, ray
intensity, calibrating of nuclear measuring equipment, thermal
exchanges, fluid circulation, irradiation effects, shielding
techniques, etc.

The swimming pool reactor is also very suitable as
a workshop laboratory for the training of nuclear personnel,
thus permitting a complete familiarization with reactor opera-
tional and safety routines such as critical assemblies, auto-
matic and manual control, protective measures for the operating
personnel, safety measures under normal operating conditions and
in case of danger, etc.

INFLUENCE OF EXPERIMENTAL PROGRAMS ON THE GENERAL DIMENSIONS OF THE SWIMMING POOL REACTOR

Faced with the wide variety of applications offered
by the swimming pool reactor, the eventual purchaser who
generally has no clearly defined experimental programs, is
tempted to purchase a highly flexible and fairly powerful reactor
affording the widest possible range of utilization. This basic
concept leads him to require a compartment swimming pool of
fairly good size, equipped with additional experimental faci-
lities. Such requirements call for a purification system and
a cooling circuit of a more complex design. Channels imply for
their utilization a working area of great dimensions at the
reactor level, hence a raised swimming pool and a very high
vessel. Should it be decided to bury the swimming pool and its
working area, this would entail huge excavations work. In
either case, however, it is necessary to shield the reactor with
thick layers of concrete. This brings out the costlier aspect
of the swimming pool reactor; yet a comparison of the small
price of this kind of reactor with others giving the same per-
formances shows that its construction costs are but "relatively"
high. But what has to be feared above all, is that in the end,
it might prove difficult to obtain full benefit from the flexi-

bility sought by a multiplication of experimental means.
Indeed, the volume of the core containing interesting fluxes has
nevertheless its limitations, and it is not favorable to divide
it into too great a number of handlings. Experience based on
a well-defined project tends to prove that a single multi-
purpose reactor is in any case advantageously replaced by two
or three more specialized reactors, operating independently,
and offering much greater experimental possibilities.

This emphasizes the importance of defining, at the
very beginning of the project, the main lines of utilization;
and in this respect, it would be primarily desirable that a
first choice be made between experimental programs with or
without channels.

As a matter of fact, in the search for economical
solutions aimed at making the facilities of the swimming pool
reactor available to users, it is worthwhile pointing out the
already extremely interesting features of a swimming pool
without channels. From then on, should a reactor without
channels be contemplated, it then becomes feasible to bury the
swimming pool and make positive savings on the construction cost;
for example, on the civil engineering of the swimming pool and
of the vessel.

It remains true, nevertheless, that some kinds of work,
those effected on beams in particular, require the use of channels.
But their initial choice, as the main experimental device, leads
to the concept of a tower-shaped reactor of smaller size, with
channels all around. Here also, we see the simplification

resulting thereof for certain parts; capacity of cooling and
of water purification, civil engineering and upper shielding,
could have a favorable effect on the construction cost.

It appears, therefore, that the preliminary choice of
a reactor, with or without channels, permits their respective
development in the best economic conditions. Should such a
choice be impossible, the set of two specialized reactors would
not, at any rate, cost more than one single multipurpose
reactor of larger size.

CONCLUSION

Because of their outstanding characteristics and
price, the swimming pool reactors more than hold their own in
the range of research reactors. Their fluxes, up to 5.10^{13} n/cm^{2}s,
hold in store tremendous possibilities of utilization. Some
manufacturers feel confident of being able to raise them to
10^{14} n/cm^{2}s, while safeguarding the safety, ease, and reliabi-
lity of operation.

The great majority of operations can be carried out
directly in the tank, the others by means of channels. Exper-
ience tends to prove the importance of separating these
functions; we should not expect the swimming pool reactor to
perform as a formidable multipurpose "robot" which we hesitate
to purchase because it is too expensive, or which we refuse
to put to maximum use because of mutual interference among the
experiments.